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An Overview of the VASIMR Engine: High Power Space Propulsion with RF Plasma Generation and Heating

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Abstract. The Variable Specific Impulse Magnetoplasma Rocket (VASIMR) is a high power, radio frequency-driven magnetoplasma rocket, capable of exhaust modulation at constant power. While the plasma is produced by a helicon discharge, the bulk of the energy is added in a separate downstream stage by ion cyclotron resonance heating (ICRH.) Axial momentum is obtained by the adiabatic expansion of the plasma in a magnetic nozzle. Exhaust variation in the VASIMR is primarily achieved by the selective partitioning of the RF power to the helicon and ICRH systems, with the proper adjustment of the propellant flow. However, other complementary techniques are also being studied. Operational and performance considerations favor the light gases. The physics and engineering of this device have been under study since the late 1970s. A NASA-led, research effort, involving several teams in the United States, continues to explore the scientific and technological foundations of this concept. The research involves theory, experiment, engineering design, mission analysis, and technology development. Experimentally, high density, stable plasma discharges have been generated in Helium, Hydrogen and Deuterium, as well as mixtures of these gases. Key issues involve the optimization of the helicon discharge for high-density operation and the efficient coupling of ICRH to the plasma, prior to acceleration by the magnetic nozzle. Theoretically, the dynamics of the magnetized plasma are being studied from kinetic and fluid perspectives. Plasma acceleration by the magnetic nozzle and subsequent detachment has been demonstrated in numerical simulations. These results are presently undergoing experimental verification. A brisk technology development effort for space-qualified, compact, solid-state RF equipment, and high temperature superconducting magnets is under way in support of this project. A Conceptual point design for an early space demonstrator on the International Space Station has been defined. Also, a parametric study of a fast (115 day,) VASIMR-driven human Mars mission has been completed. This paper reviews the progress obtained in all these areas and outlines plans and strategies for continued research.

INTRODUCTION

The chemical rocket is today our primary means of space transportation; however, its inherent limitations in payload capacity and speed have stimulated a renewed interest in advanced rockets, capable of much higher performance. One such device is the Variable Specific Impulse Magnetoplasma Rocket (VASIMR,) currently under development by NASA[1]. Its genesis dates back to the late 1970s when a low level effort to study its characteristics began at the Charles Stark Draper Laboratory and the Massachusetts Institute of Technology. The system borrows heavily from fusion research, particularly in open-ended devices; however, not being a fusion concept, its plasma parameters are substantially relaxed. This enables an early deployment and allows the development effort to focus on the difficult enough task of space-borne qualification. In the early 1980s, NASA and the US Air Force Office of Scientific Research initiated a small experimental program at the MIT Plasma Fusion Center. This activity formulated the fundamental physics questions that had to be addressed and laid the groundwork for the present effort. The research was relocated in 1993 to the Johnson Space Center in Houston, where it has evolved into a strong multilateral activity involving 8 major universities, private industry and two DOE laboratories. Present results point to a rapid space test on the International Space Station as the first stepping-stone in a brisk technology development effort to enable rapid interplanetary access in the next decade.

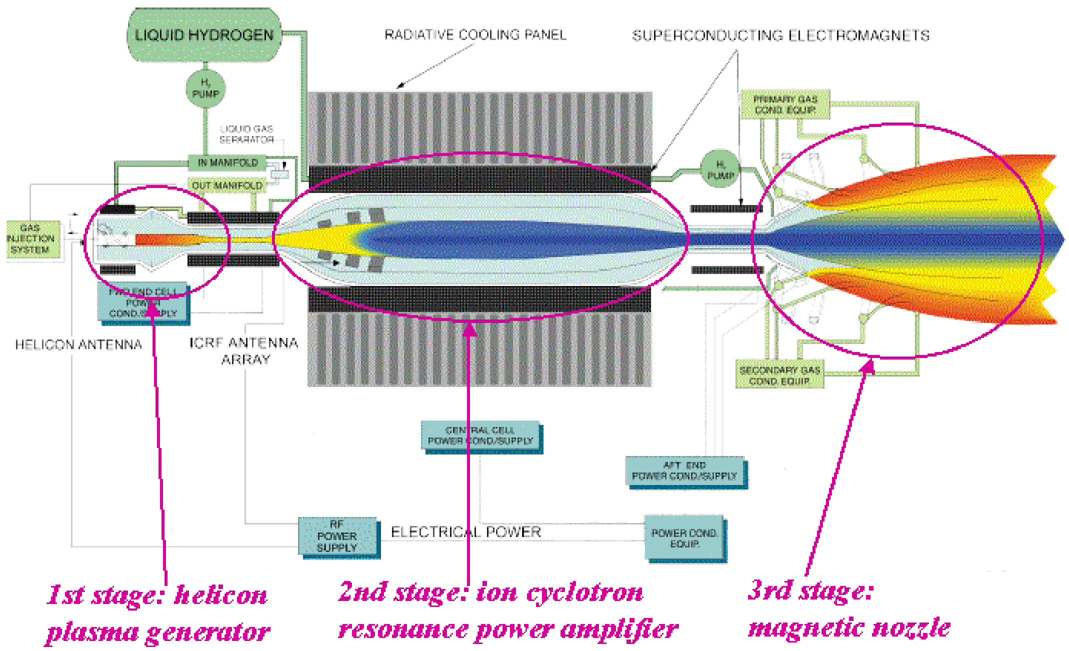
SYSTEM DESCRIPTION

The VASIMR system, shown in Figure 1a, has both electrothermal and electro-magnetic features. Energy is delivered to the plasma via a collisional process sustained by direct RF heating of the plasma electrons (electrothermal) with subsequent ion acceleration through ion cyclotron resonance (electromagnetic.) The system is capable of high power density, as the plasma energy is delivered by wave action, making it electrodeless and less susceptible to component erosion.

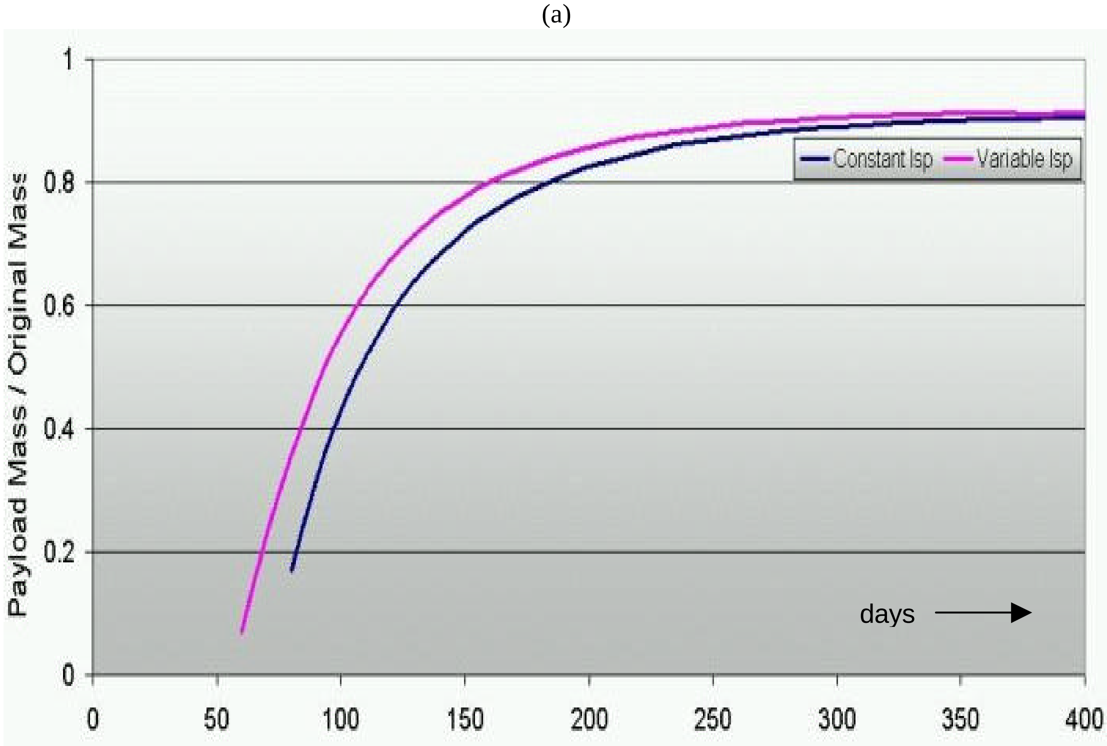
While simpler configurations are being considered for early deployment, the full VASIMR configuration of Figure 1a illustrates the wide array of features embodied in the concept. The system consists of three linked magnetic stages, where plasma is respectively injected (1st stage,) energized (2nd stage) and expanded (3rd stage.) The 1st stage is a helicon source, which ionizes the propellant gas (typically hydrogen, deuterium, helium, or gas mixtures); the 2nd stage uses ion cyclotron resonance heating (ICRH) to store ion kinetic energy in the form of perpendicular motion. Rocket thrust at high exhaust velocity is obtained in the 3rd stage by adiabatic expansion of the plasma in a magnetic nozzle.

An important characteristic of the VASIMR is its capability to vary its exhaust parameters at constant power. This principle, known as constant power throttling (CPT,)[2] optimally tunes the rocket to the conditions of flight. In practice, CPT involves trading off exhaust velocity (also known as specific impulse, I_{sp}) for thrust. For short trip times, the variable I_{sp} rocket achieves substantial payload improvement over its constant I_{sp} counterpart, as evidenced by Figure 1b.

The variability of the exhaust comes primarily from power management to both the helicon and ICRH systems. For high thrust, RF is predominantly fed to the helicon, while for high I_{sp} more power is diverted to the ICRH system with concomitant reductions in thrust. Other methods are being explored, including the use of a magnetic choke at the exhaust cell to keep some of the plasma longer within the power amplification section (2nd stage) and increase its energy content. Less plasma would then exit the rocket, but at a higher velocity.



(a)



(b)

Fig. 1. Schematic of the VASIMR system (a), and a trip comparison (b) of constant (lower trace), vs. variable (upper trace) specific impulse, for a characteristic one-way high-energy mission to Mars.

For high thrust maneuvers, in a high gravity environment, a “plasma afterburner” could be created by the injection of a hypersonic coaxial boundary layer of neutral gas within the nozzle. The gas increases the total mass flow and may recover some of the frozen ionization energy in the form of gas kinetic energy. The presence of the gas also enhances plasma detachment from the magnetic field by collisional diffusion. Investigators from the Princeton Plasma Physics Laboratory and the NASA Marshall Space Flight Center[3,4] are currently studying this process.

EXPERIMENTAL STUDIES

Experimental research on the VASIMR is being conducted in three similar and complementary experiments in the US. The largest one is the VX-10 device located at the NASA Johnson Space Center in Houston Texas. Two smaller experiments: the Linear Device at The University of Texas at Austin and the Small Radio Frequency Test Facility, known as the “Mini-RFTF”, at The Oak Ridge National Laboratory (ORNL) support these investigations. A synoptic view and recent photograph of the VX-10 device are shown in Figs. 2a and 2b.

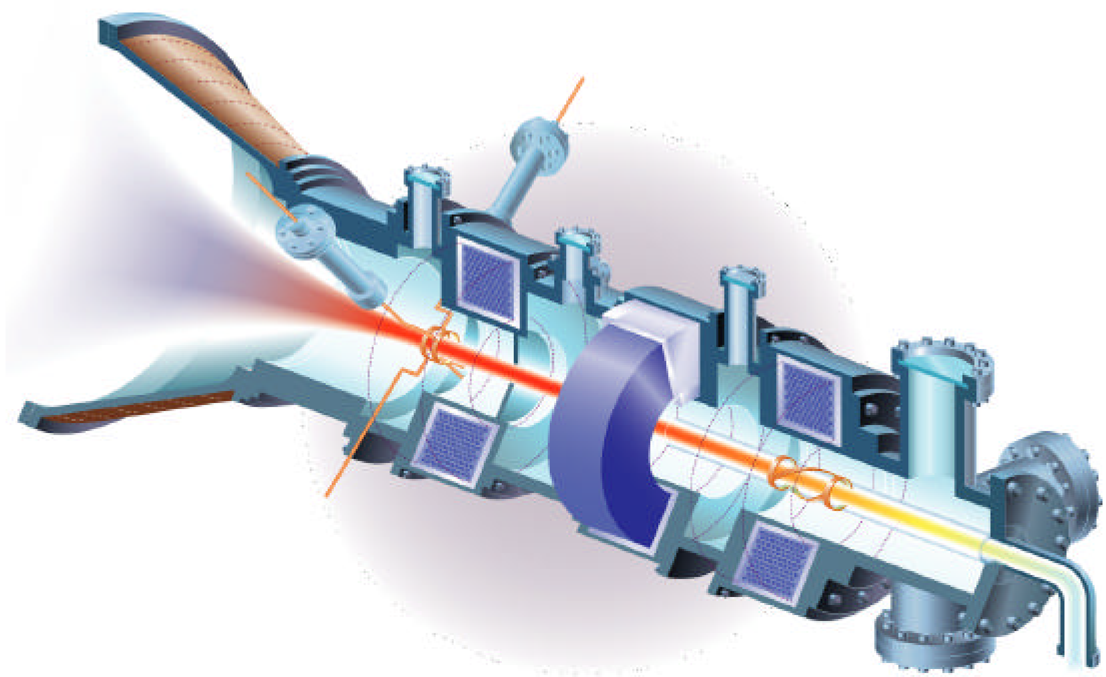


Figure 2a. Synoptic view of the VX-10 laboratory experiment at the NASA Johnson Space Center.

High-density ($>10^{18}/m^{-3}$) steady-state discharges in hydrogen, helium, deuterium and argon have been obtained from the helicon injector in the VX-10 device. The present configuration features a quartz tube mounted on a stainless steel support and housing the bleed orifice through which the gas is metered. The tube is threaded through a water-cooled helical antenna. The best performance is obtained with a strong magnetic mirror “choke” field (≈ 1.0 Tesla) located downstream of the tube exit and a relatively high gas pressure (≈ 10-30 mTorr) within the quartz tube.

When the discharge occurs, a Baratron gauge located at the gas injection point measures a rapid total pressure increase. This pressure rise is shown in Figure 3a and is clearly associated with the presence of the plasma. A dip in the total pressure at about 1500 ms is due to plasma cooling caused by the insertion of a Mach probe (a relatively large thermal sink.) The time evolution of the exhaust chamber pressure shows the rise in background pressure during the discharge and indicates the limitations of the present vacuum system. During the discharge, the pumping effect of the plasma, as shown in Figure 3b is also evident.

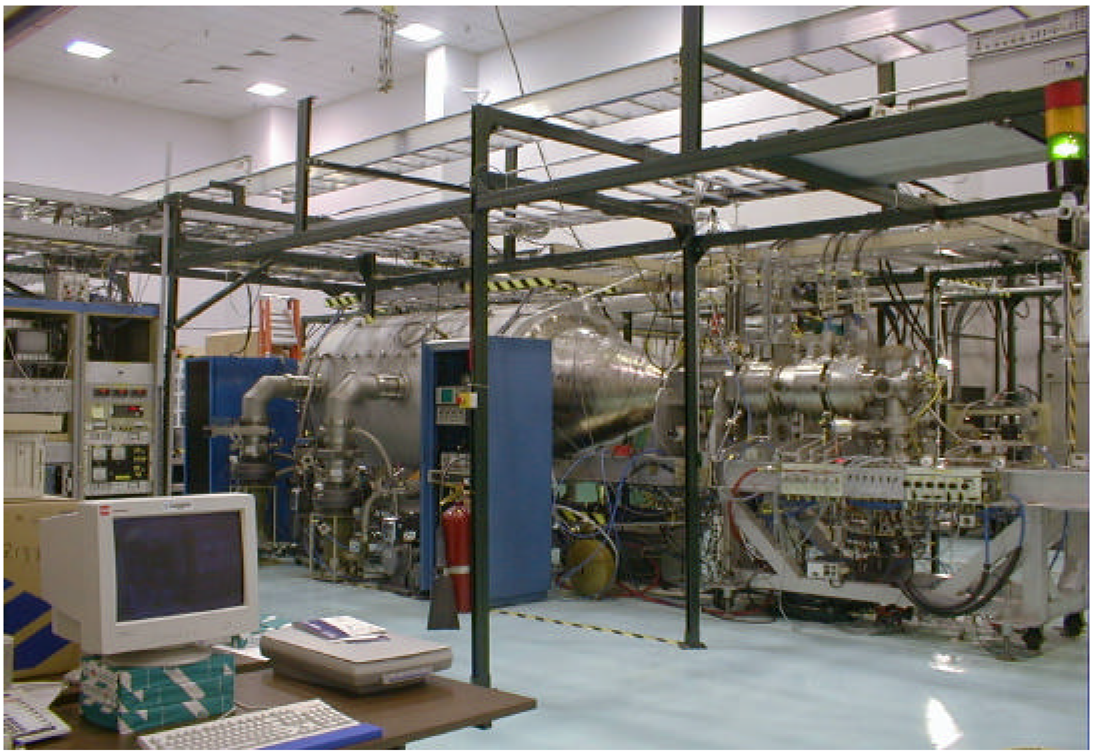
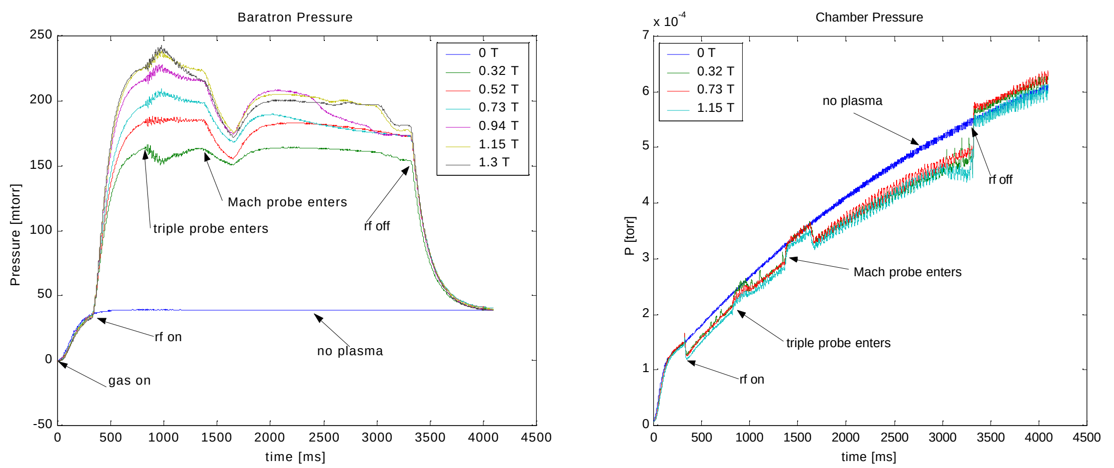


Figure 2b. Recent photograph of the VX-10 experiment in a 3-magnet configuration. A 4th magnet has been added to produce a shallower field at the ICRH resonance.

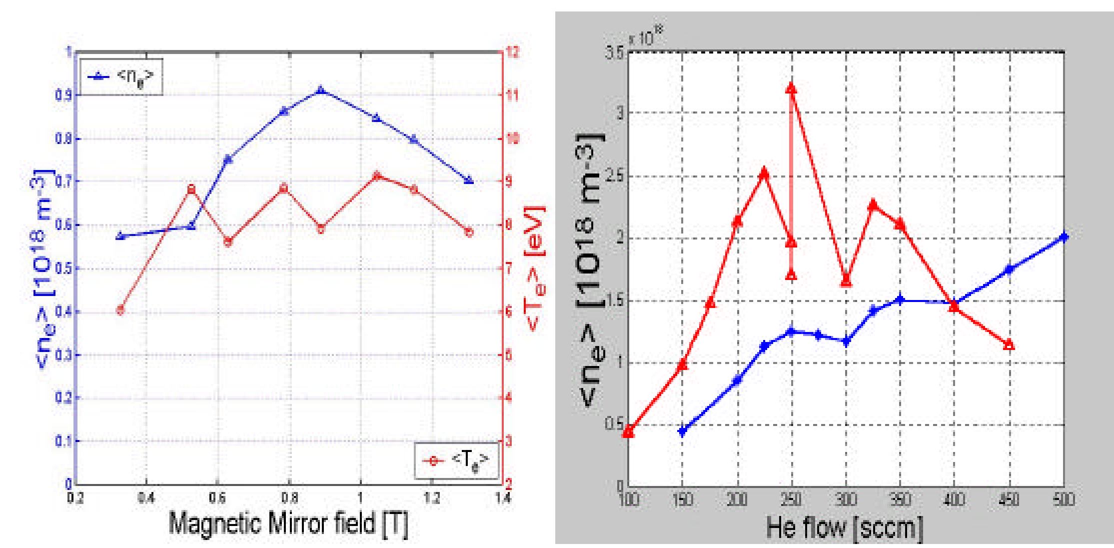
Under the best conditions, the discharge near the tube exit is well detached from the wall. Sputtering at the upstream injection flange had been observed at low gas flow rates; however, this effect has been virtually eliminated by a high density gas “cushion,” which cools the plasma before it can reach the flange. For a given tube diameter, the plasma performance also increases with tube length, suggesting the benefit of a neutral “gas box” to maintain a high pressure near the helicon antenna. Plasma density and electron temperature as functions of the mirror “choke” magnetic field are shown in Figure 4a for helium, while Figure 4b shows the effect of lengthening the quartz tube from 76.2 cm to 106.68 cm.

In all cases, the plasma past the choke accelerates to supersonic speeds, while the flow upstream of the choke remains subsonic. The flow velocity and Mach number for helium, as measured with a reciprocating Mach probe are shown in Figures 5a and 5b at points upstream and downstream of the choke respectively. Flow velocities of 15 km/sec are quite common and encouraging, as they indicate a respectably high specific impulse even before ICR heat addition. Recent deuterium data show even faster flows.



(a) (b)

Figures 3a and 3b showing the time evolution of the pressure at two points in the system: 3a, the Baratron gauge, measuring the rapid pressure increase associated with the plasma turn on and 3b, the fast ion gauge, measuring the total background pressure in the discharge chamber and showing evidence of plasma pumping.

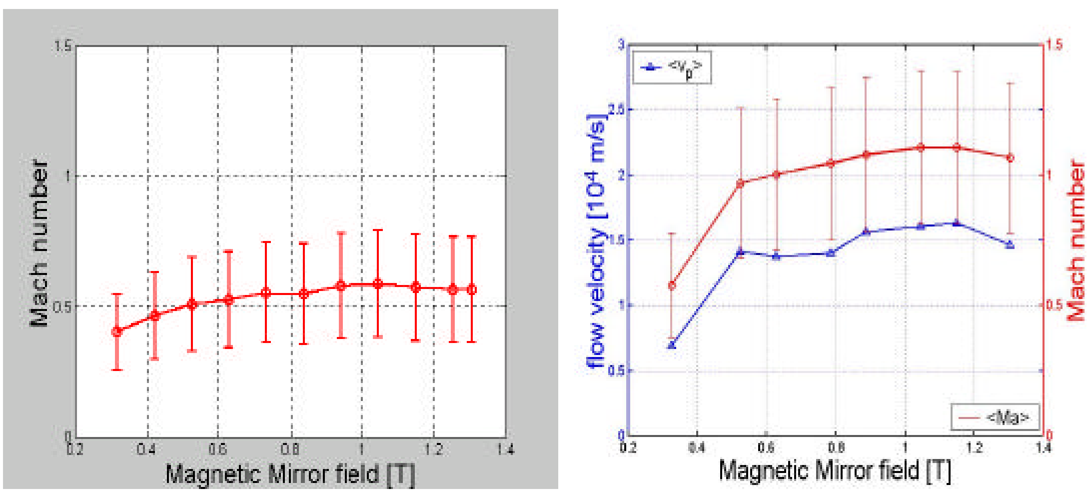


(a) (b)

Figures 4a and 4b show: (a) the performance increase with choke magnetic field and (b) the effect of two quartz tube lengths at 76.2 cm (lower curve) and 106.68 cm (upper curve)

In these discharges, the charge exchange reaction is ubiquitous and probably responsible for any heat loading on the quartz tube wall; however, localized heating has also been observed at various axial locations where we suspect the magnetic field lines glance into the material; further studies on this effect are ongoing; however, the maximum temperatures observed do not exceed about 600^{o}C. Macroscopically, the plasma shows a very well defined shape with no apparent gross instability. A recent photo of a high-density deuterium discharge is shown in Figure 6a.

Recent experiments[5] with gas mixtures show the existence of a high-energy tail on the minority component. These measurements have been obtained with two separate retarding potential energy analyzers. The results are shown in Figure 6b for mixtures of 10% hydrogen on helium. Fitting of the data show two drifting Maxwelian distributions at velocities of ≈ 35 km/sec for helium and ≈ 150 km/sec for hydrogen. Similar behavior has been observed in experiments with deuterium-hydrogen mixtures. The acceleration mechanisms for these high velocities are not fully understood and are the subject of intense study by our research team. This intriguing behavior may point to still another “knob” for exhaust variation.



(a) (b)

Figures 5a and 5b show the Mach number and plasma flow velocity at points (a) upstream and (b) downstream of the magnetic choke.

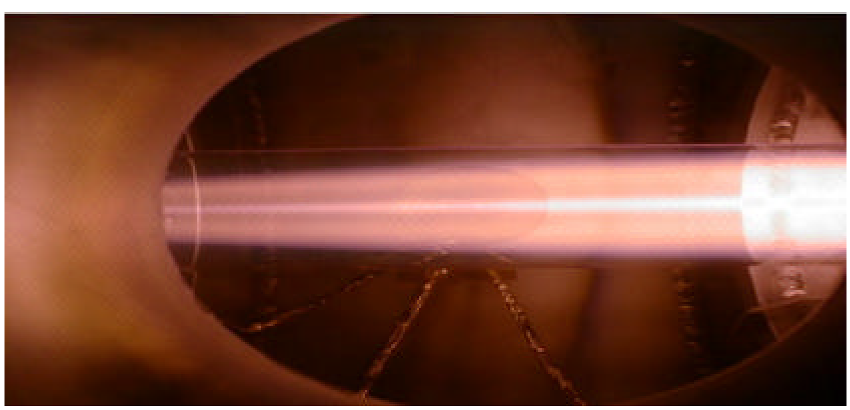


Figure 6a: VX-10 helicon helium plasma discharge firing from right to the left into the “choke” field

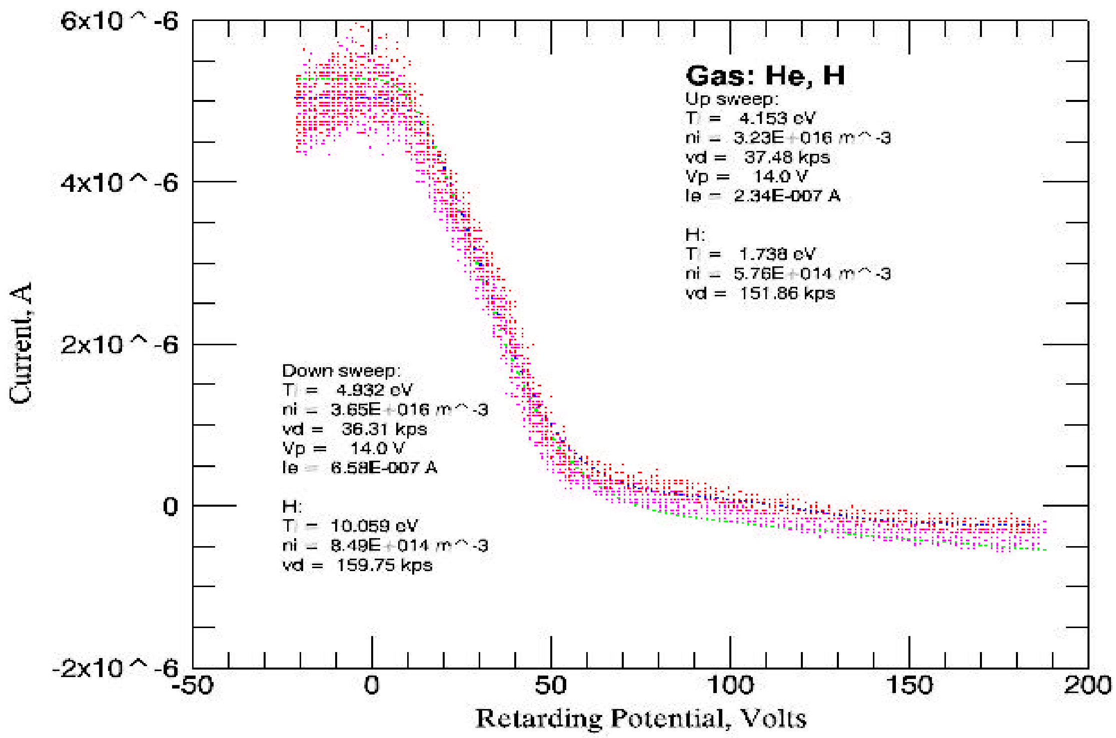


Figure 6b: Retarding potential analyzer data for mixtures of 10% hydrogen on helium showing a high energy tail with velocities in excess of 150km/sec.

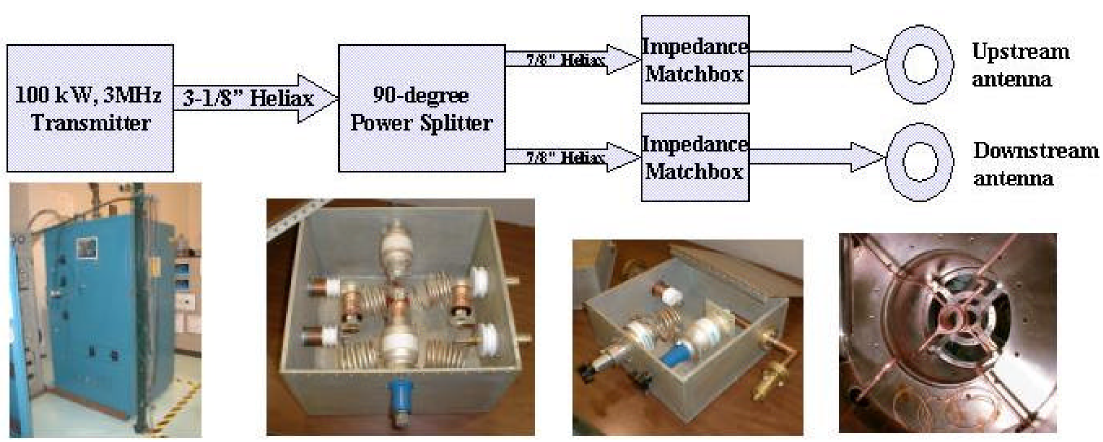


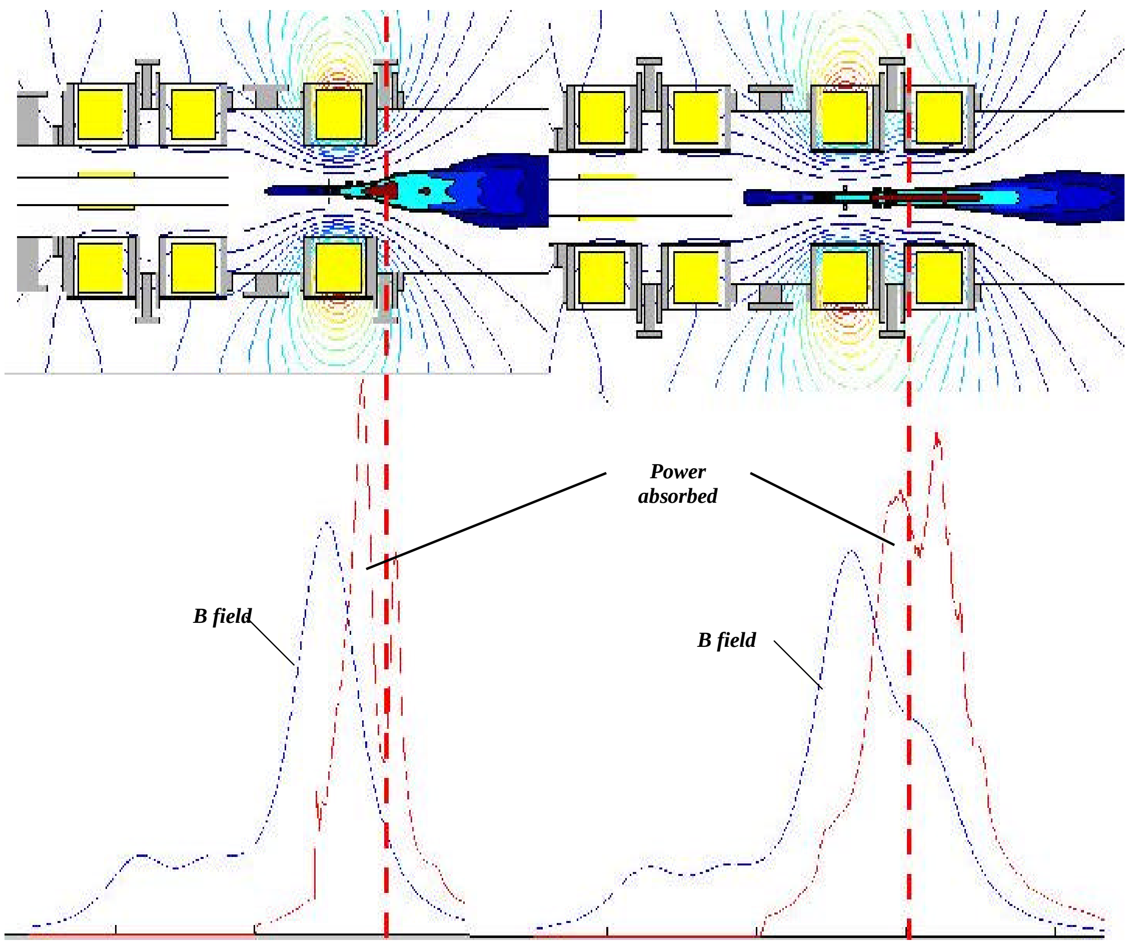
Fig. 7. Ion cyclotron resonance system architecture

While the helicon source continues to be optimized, experimental studies of the ICRH stage are getting under way. Critical components have been manufactured and are undergoing installation and testing. These components include the RF generators, transmission lines, matching and protection circuits and RF antennas. Two double half-loop antennas are driven independently with a 90^{o} phase shift from a single source. The system architecture is shown in Figure 7. Total power capability will be 10kW initially with future upgrade capability to 100kW.

THEORETICAL STUDIES

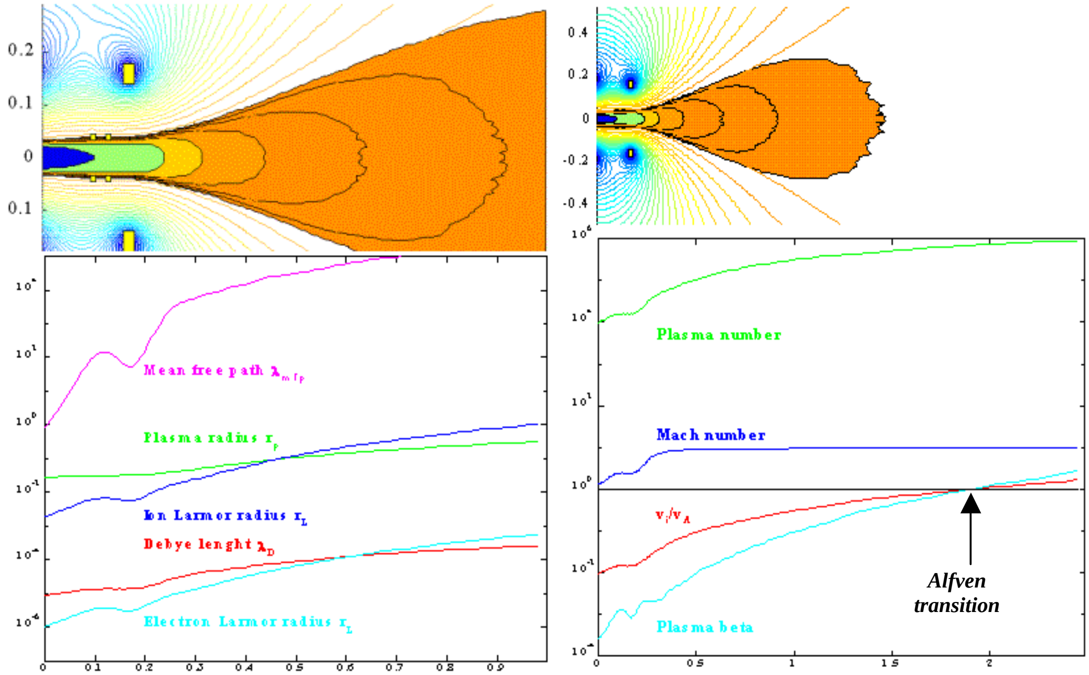
Many important aspects of VASIMR physics are being addressed in complementary theoretical studies and simulations[6,7]. For example, our present ICRH strategy is based on results of a hybrid wave-particle code. These predict improved RF absorption with the addition of a fourth magnet to the stack, creating a shallower magnetic beach near the resonance. Simulation results are shown in Figure 8a.

The issue of plasma detachment from the ship's magnetic field after the expansion centers on the rapid increase of the local plasma β as the flow moves along the field. Recent theoretical calculations[8,9] consider the detachment problem by looking at the transition from sub-alfvenic to super-alfvenic flow. This perspective resembles the sub-sonic to super-sonic transition in a Laval nozzle, beyond which the dynamics upstream are decoupled from the downstream conditions. The Alfven transition in the present configuration takes place about 2m downstream of the magnetic throat, as shown in Figure 8c. Experiments are being planned to study these physics.



(a)

Fig. 8a. The addition of a 4th magnet improves the absorption by adding a shallower gradient to the magnetic field over the 3-magnet configuration.



(b) (c)

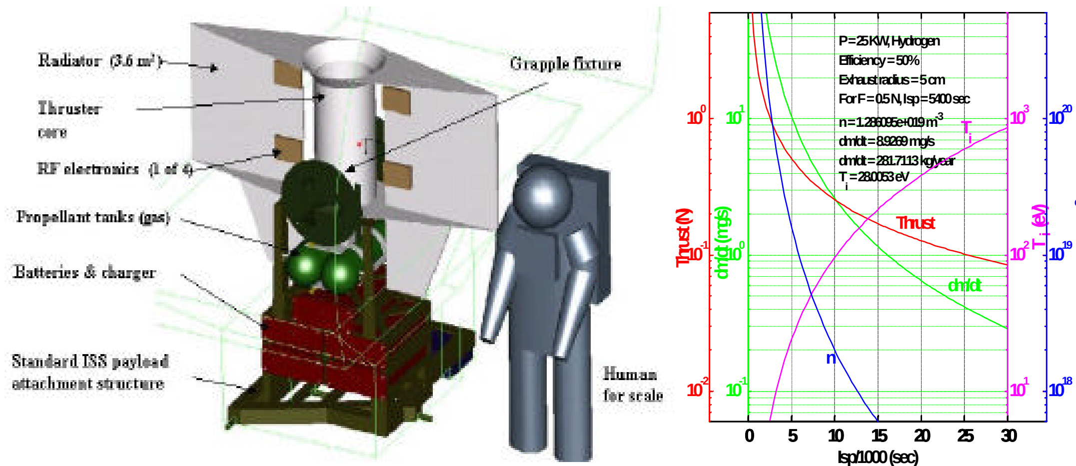
Fig. 8 (b,c). Scaling parameters are shown in the near (b) and far (c) field of the VASIMR plume. Alfven transition (c) occurs 2m downstream from the magnetic throat.

ENGINEERING AND TECHNOLOGY DEVELOPMENT

Important engineering aspects are being considered in concert with the development of the physics. For example, the utilization of cryogenic propellants such as hydrogen and helium will lend itself to regenerative thermal designs. Advanced heat pipes, high temperature superconductors and new solid-state RF amplifiers are some of the new technologies being considered. Rapid experimental deployment of an early VASIMR design is also being sought on the International Space Station (ISS), which offers a unique environment to test these systems. An experimental VASIMR operating at 25kW could provide about .5 N of thrust at a specific impulse of 5400 sec. The system could operate on deuterium or hydrogen. The later one could be scavenged from the present life support system of the ISS, where it is treated as waste, eliminating propellant orbit transportation costs. A bonus from this test results since the total thrust exceeds the ISS atmospheric drag, thus VASIMR could become a drag compensation device, eliminating the high cost of chemical reboost for the facility. A preliminary conceptual design, shown in Figure 9a, has been completed showing the feasibility of such a test. The expected performance envelope for this system is shown on Figure 9b.

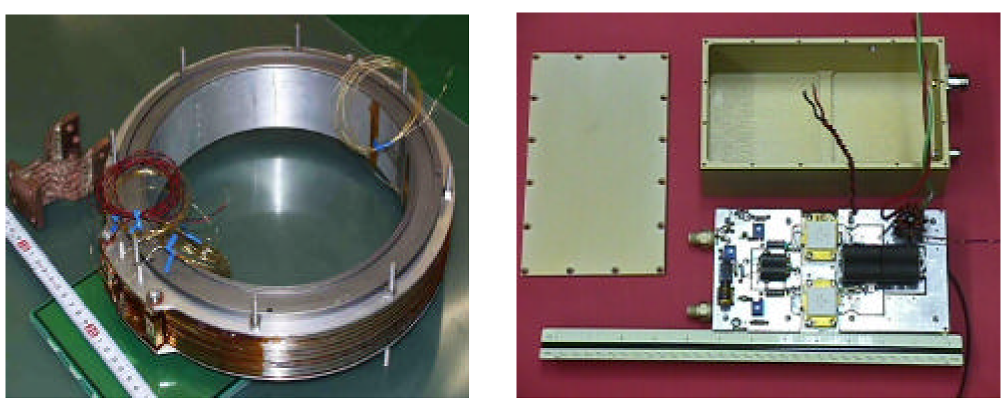
Taking advantage of the space environment, the VASIMR uses high temperature superconductors to produce its required magnetic field. Passive thermal control can be achieved with proper radiation shielding, as the natural vacuum of space also insulates these components. Advanced designs would also have regenerative cooling by the propellant itself, liquid hydrogen. At present, lightweight superconductors based on

Bismuth Strontium Calcium Copper Oxide (BSCCO) compounds are being designed for this application and have reduced the weight of these components by an order of magnitude. Continuing advances in this technology bode well for even lighter designs. The first flight-like VASIMR BSCCO magnet, shown in Figure 10a, is being integrated into the existing VX-10 experiment to replace one of the conventional 150kg copper magnets. At only 5kg, it produces a .28 Tesla field on axis at a temperature of 40°K.



(a) (b)

Fig. 9. Conceptual design (a) of the first VASIMR space experiment for the International Space Station. The performance envelope (b) shows propulsion parameters as functions of the specific impulse.



(a) (b)

Fig. 10. The high temperature BSCCO superconducting magnet (a) will be integrated in the VX-10 device downstream of the ICRH section. A solid state 1 kW RF amplifier (b) has been developed as the building block of the RF system.

Miniaturization of the RF equipment is another important goal. To this end, the research team has been working with high-power, solid-state transistor technology to achieve suitable lightweight amplifier designs. Two 1 kW RF modules such as the one on Figure 10b have been built and are being evaluated. Clusters of these units are being considered as the building blocks for both the helicon and ICR systems. The architecture will be based on robustness and reliability.

MISSION APPLICATIONS

Operationally, the high thrust mode of the VASIMR can be employed in the early stages of orbital boost. As the vehicle escapes the gravitational pull, its exhaust gradually transitions to a high I_{sp} mode, continuing to accelerate the craft. The reverse applies as the ship approaches its destination. For planetary fly-by, or deep space missions not requiring orbital insertion, the engine closely matches vehicle and exhaust velocities for optimum propulsive efficiency. Other operational benefits include efficient round-trip capability to the high-energy commercial orbits in the Earth-Moon environment, as well as satellite refueling, maintenance and repair.

VASIMR technology enables very fast human planetary transits to Mars and beyond. The short trip time reduces exposure to microgravity and the crew's physiological de-conditioning. Moreover, the liquid hydrogen propellant provides an effective radiation shield. A conceptual 115-day mission to Mars is shown in Figure 11. Fission reactors with a total electric power of 12MW power the spacecraft. Such power-rich architectures are essential for human survival, enabling mission abort capabilities.

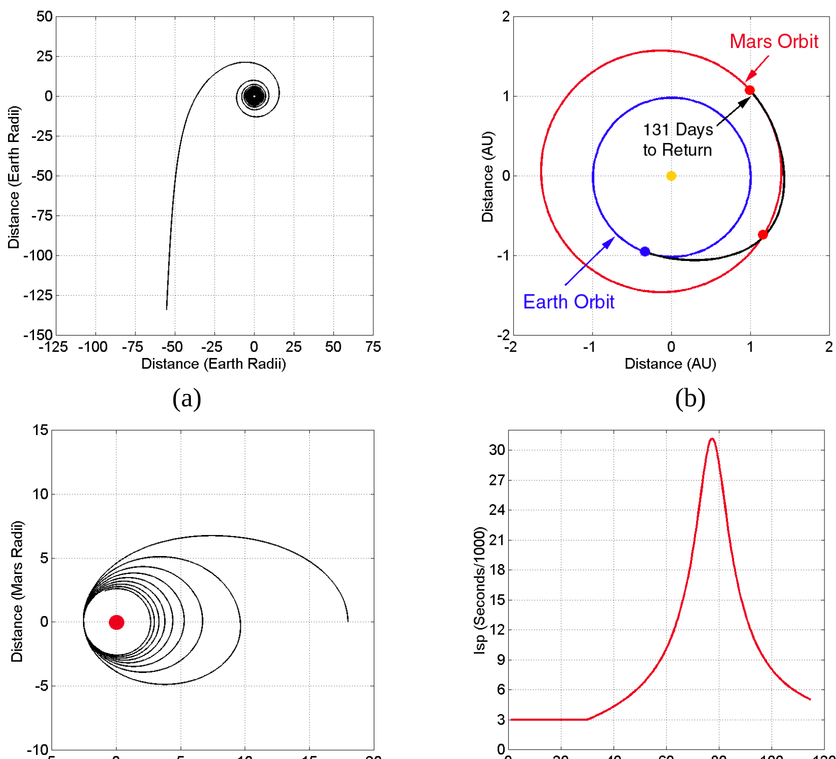


Fig. 11. VASIMR human Mars mission. The 188 mT piloted ship departs Earth orbit and climbs on a 30-day spiral (a) followed by a heliocentric trajectory to two Mars encounters at 85 and 216 days respectively (b). The crew lands on the first encounter, while the mother ship continues on to the second encounter and gradually spirals into low Mars orbit (c) to await the completion of the surface mission. The I_{sp} schedule (d) delivers the craft for aerobraking at Mars at a relative velocity of 6.8 km/sec.

CONCLUSSIONS

For the future, the possibility of achieving fusion within the plasma itself would increase the power of VASIMR several fold, leading to even faster trips. The thrust levels would be much higher and continuous, resulting in a substantial artificial gravity. While controlled fusion remains elusive, efforts to achieve it have been relentless and the progress steady. Building on this progress, the VASIMR provides an evolutionary path for further technology growth, but with exciting and immediate applications en-route. With fusion rockets, the possibilities are truly awesome, and fully worth our continued study. Our future generations will use these systems for rapid access to the solar system and ultimately the stars. We now find ourselves preparing the groundwork for their eventual success.

ACKNOWLEDGEMENTS

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